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EVALUATION OF AN ANALYTICAL MODEL FOR  
PREDICTING LIGHT SCATTERING FROM CYLINDRICALLY  
SHAPED OBJECTS IN THE OCEAN

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## **Evaluation of an Analytical Model for Predicting Light Scattering from Cylindrically-Shaped Objects in the Ocean**

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**RESEARCH GOALS:** The long term goal of this project is to understand and quantify the consequences of light scattering from ensembles of cylindrically or other irregularly shaped objects with varying degrees of orientation on the optical properties of the ocean and the transmission of polarized light through sea water.

**OBJECTIVES:** The primary objective of the project is to evaluate the coupled-dipole method as an analytical model to predict the scattering of electromagnetic radiation from a collection of randomly oriented cylindrically-shaped micro-organisms in the ocean. Secondly, in a collaborative effort with A.J. Hunt of Lawrence Berkeley Laboratory and M.S. Quinby-Hunt of University of California, the effects on the transmission of light through sea water caused by the orientation of ensembles of cylindrical particles will be examined by studying the symmetry and angular variability of scattering matrix elements determined by the coupled-dipole method.

**APPROACH:** In order to describe the scattering of light from marine organisms of other than the simplest shapes (i.e. spheres, very long cylinders, etc.), it is necessary to resort to approximate methods. The coupled-dipole model, developed by Purcell and Pennypacker<sup>1</sup> in 1973 has been chosen for this project for two important reasons: (1) an organism of any shape can, at least in principle, be modelled, and (2) all sixteen elements of the Mueller scattering matrix can be calculated. The electric field at each dipole position is a critical calculation in this model. Unfortunately, a direct solution of the electric field at each dipole requires the inversion of a  $3N \times 3N$  matrix with complex coefficients for an object modelled by  $N$  dipoles. This is a formidable task for a computer both in terms of storage requirements and processing time, and many researchers have abandoned the coupled-dipole approach for this reason. We have attempted to overcome this obstacle with two different approaches; (1) the use of a 'super computer' for carrying out the necessary computations of the direct inversion of a matrix, and (2) the use of the scattering order approximation technique for matrix solution developed by Singham and Bohren<sup>2</sup>. For the first approach, we used the Cyber 205 fast computer at the Advanced Computational Methods Center (ACMC) at the University of Georgia for carrying out the computations. The storage requirement limits the number of dipoles that can be modelled to about 500. For the second approach, we used a microVax 2000 provided to this project by A.J.Hunt. The scattering order approximation is appropriate for

the microVax since this method does not require the storage of a large matrix. The disadvantage of this method is that the solution does not converge for large size parameters and/or large refractive indices. The relative index of refraction of most marine organisms is close to one and does not present a major obstacle, however, their size parameters are generally large and this proved to be a limiting factor when using this approach.

**TASKS COMPLETED:** Three tasks were completed during this year;  
 (1) A computer code for the Cyber 205 was written for calculating the elements of the scattering matrix of a single object at any orientation.

(2) A computer code for the scattering order approximation was obtained for the microVax from Cliff Dungey and Craig Bohren at Pennsylvania State University with the matrix solution section of the program written by Shermilla Singham. This program included subroutines for calculating the dipole positions for a sphere, an ellipsoid, a rectangular solid, and a cylinder. TSU students added subroutines for a 14-strand thick helix and a single strand helix to the shapes modelled.

(3) The computer code for the scattering order approximation was modified to include the averaging of the scattering effects due to an ensemble of identical particles over random orientations.

**RESULTS:** The results of the computer computations are best presented graphically. In the interest of simplicity, we have limited the graphs for a single particle to the normalized  $S_{14}$  Mueller matrix element. This element is associated with the depolarization of circularly-polarized light, and potentially is important for underwater imaging and detection systems. The dramatic effects on the  $S_{14}$  element of even small changes in size parameter of a cylinder are shown in Fig.1. The 'equivalent' size parameter is defined here to be  $2\pi$ ( 'sphere' radius/wavelength); where the equivalent 'sphere' is a sphere having the same volume as the cylinder of interest. The largest size parameter we were able to handle on the microVax was about 7.0 due to excessively long computation time. However, it is the size parameter of the dipole region and not the cylinder that is the critical factor in the convergence of the scattering order approximation. Figs.2(a) and 2(b) show the variations in  $S_{14}$  for several different orientations of a single cylinder and a thick helix, respectively. Fig.3 displays all 16 elements of the Mueller matrix as a function of scattering angle for a collection of randomly oriented cylinders. An important result is the non-vanishing  $S_{14}$  element. The values of  $S_{14}$  are small, generally less than 5% of the total intensity, but detectable experimentally. The structure of the  $S_{14}$  is clearly a cylinder 'edge' effect and not due to the roughness of the model or crudeness of the averaging calculation. All the matrix elements for a sphere and an ellipsoid using the same computer program are smoothly varying or identically zero.



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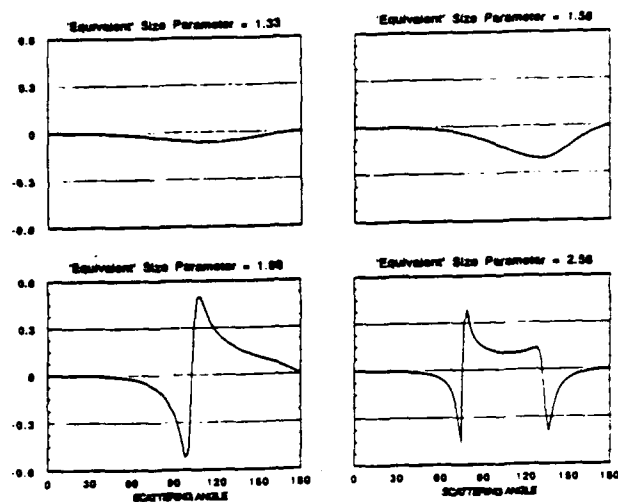
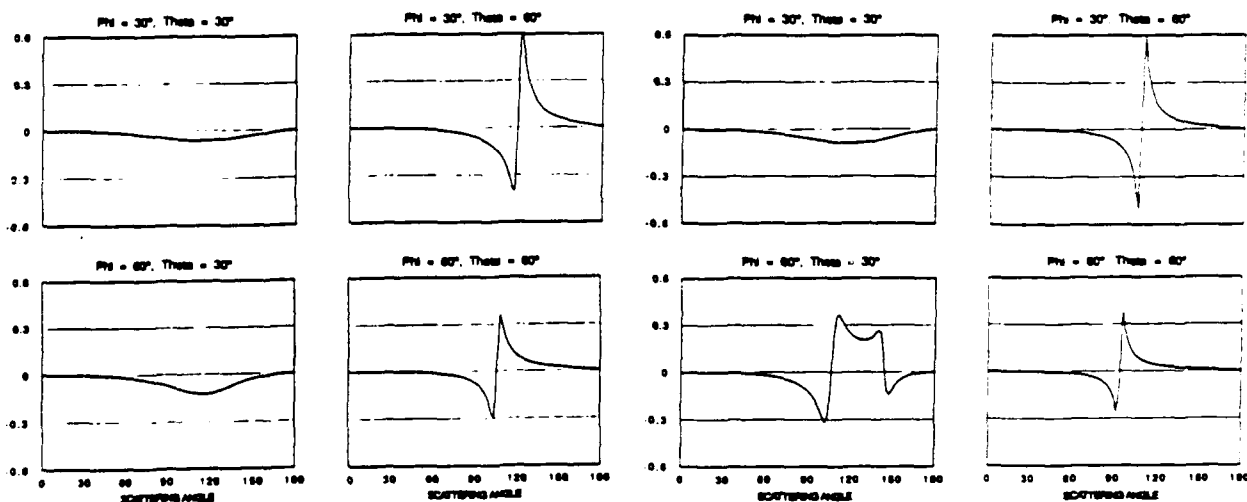


Figure 1. The normalized S14 Mueller matrix element for a single cylinder with a size parameter of 1.3 and length to diameter ratio of 1.6. The cylinder is oriented at  $\phi=30^\circ$  and  $\theta=30^\circ$ . (See Fig.2)



(a) Cylinder

(b) Thick Helix

Figure 2. The normalized S14 Mueller matrix element. Both the cylinder and the helix have a length to diameter ratio of 1.6 and a size parameter of 1.3.  $\phi$  is the angle between a coordinate axis and the projection of the object's axis in the scattering plane, and  $\theta$  is the angle between the object's axis and the incoming light.

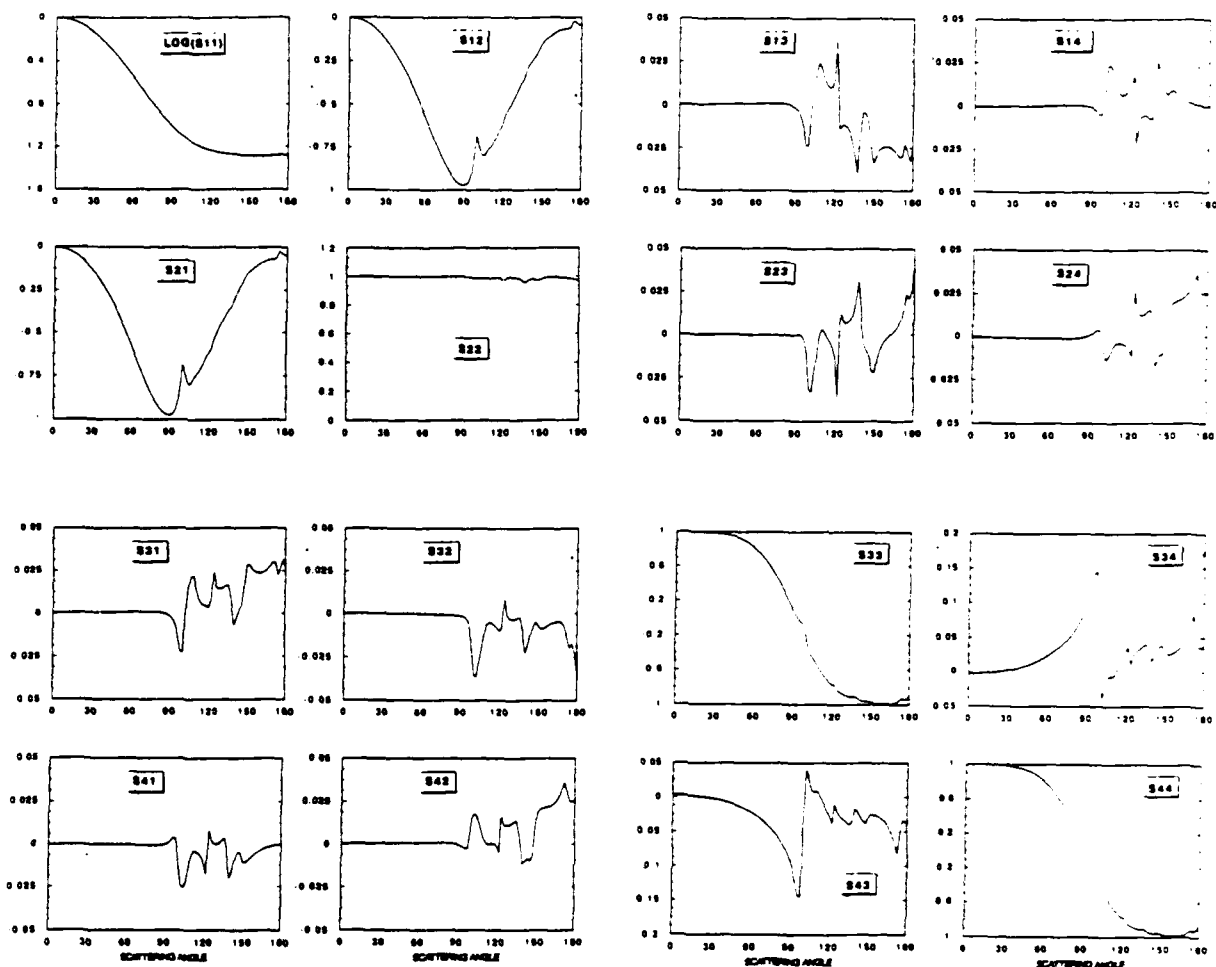


Figure 3. The 16 elements of the Mueller matrix for a collection of randomly oriented cylinders. Cylinders are identical with a size parameter of 1.3 and a length to diameter ratio of 1.6.

#### PRESENTATION:

Abstract titled: "Coupled-Dipole Approximation as an Analytical Model for Predicting Light Scattering from Marine Micro-Organisms," was accepted for 1990 Fall Meeting of the American Geophysical Union in San Francisco.

#### REFERENCES:

1. Purcell, E.M. and C.R. Pennypacker. "Scattering and Absorption of Light by Nonspherical Dielectric Grains," *Astrophys. J.* **186**, 705 (1973).
2. Singham, S.B. and C.F. Bohren. "Light Scattering by an Arbitrary Particle: the scattering-order formulation of the coupled-dipole method." *J. Opt. Soc. Am.* Vol 5, No. 11, March 1986.